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Fabrication and properties of piezoelectric composites designed for process monitoring of cement hydration reaction

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ABSTRACT

A series of receiving type piezoelectric composites were designed and fabricated by cutting and filling technique. The piezoelectric composites were also optimized from such aspects as matrix phase, functional phase and composite connectivity. The researches show that these piezoelectric composites have larger piezoelectric voltage factor, thickness electromechanical coupling coefficient and lower acoustic impedance than the pure piezoelectric ceramic. The early cement hydration reaction process monitoring result indicates that the ultrasonic wave receiving ability of the piezoelectric composite is obviously better than that of the pure piezoelectric ceramic. Therefore, these kinds of piezoelectric composites have potential application prospect in cement hydration reaction process monitoring.

1. Introduction

Cement is an important building material whose hydration and hardening processes are very complex. As one of the most important components of concrete, the hydration characteristics of cement determine many important physical properties of concrete structures. Therefore, the researches of formation and development of cement paste structure have great significance in improving the comprehensive properties of concrete.

Cement will generate kinds of hydrated products in different hydration periods, which leads to variations of density and elastic modulus of cement hardened paste. It is known that the propagation speed of ultrasonic wave in the medium is related to the density, elastic modulus and Poisson's ratio of the medium. Therefore, the cement hydration reaction process can be monitored by analyzing the variation behavior of waveform and related parameters of ultrasonic wave which propagated in the cement paste [1–3]. However, ultrasonic wave is a kind of mechanical wave contained complex frequency components, which can propagate in mediums of solid, liquid and gas, so it will inevitably be reflected and refracted when propagating in them. Cement paste can be regarded as a kind of high frequency filter, especially in the early hydration reaction period of cement, the ultrasonic wave will have serious energy attenuation because of the influences of cement particles and interface between cement paste and ultrasonic transducers, so the process monitoring ability of cement hydration reaction based on ultrasonic wave technology will decrease correspondingly.

Currently, there is still no special ultrasonic transducer for the process monitoring of cement hydration reaction. Usually, the scholars monitor the cement hydration reaction process depending on the ultrasonic testing equipment in concrete non-destructive fields. However, the ultrasonic transducers in civil engineering fields have many disadvantages, such as metal shell, mismatched acoustic impedance with cement materials and low frequency band, which limits their applications in cement hydration reaction process monitoring. Therefore, it is very important to develop a kind of embedded ultrasonic probe with the characteristics of high sensitivity, broad frequency band and good interface/acoustic impedance matching abilities with cement materials.

Piezoelectric composites are gaining more and more popularity because of their many superior characteristics [4,5], and many scholars have also proposed kinds of new ideas to improve the comprehensive properties of piezoelectric composite [6–8]. Recently, according to the health monitoring requirements of civil engineering structure, some scholars have developed a new type of intelligent material, that is, cement based piezoelectric composite [9–14]. Their researches show that this kind of composite has not only good sensing and driving abilities, but also superior interface and acoustic impedance matching abilities with concrete materials, which shows potential application prospect in civil engineering fields [15–17]. In view of this, a series of embedded piezoelectric composites were designed and fabricated by considering such aspects as matrix phase, functional phase and composite connectivity. The properties of these piezoelectric composites were also tested in order to obtain the optimal ultrasonic wave receiving ability for cement hydration reaction process monitoring.

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Table 1
Main raw materials and their properties.

	K_p (%)	K_t (%)	d_{33} (pC N^{-1})	tan δ	ε_r	Q_m	ρ (10^3 kg m^{-3})	S_{11}^E ($\times10^{-12}$ m^2 N^{-1})	S_{33}^D ($\times10^{-12}$ m^2 N^{-1})
Portland cement	–	–	–	0.780	25.9	–	2.20	–	–
PZT-4	58	48	260	0.003	1050	800	7.5	12.0	6.8
PZT-5	62	50	600	0.02	2200	80	7.6	16.7	8.9

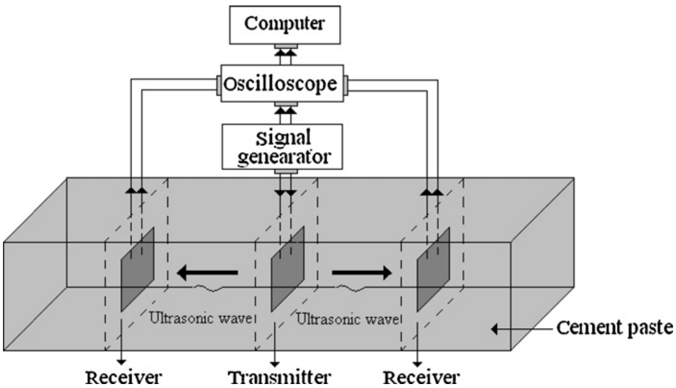

Fig. 1. Monitoring sketch map of cement hydration reaction process based on ultrasonic wave technique.

2. Experimental procedures

2.1. Raw materials

In this research, Portland 42.5 cement (Shandong Cement Factory, China), lead zirconate titanate piezoelectric ceramic PZT-4 and PZT-5 (Shandong Zibo Yuhai Ceramic Factory, China) were adopted, respectively. Their basic properties are shown in Table 1.

Besides, bisphenol A epoxy resin (Shandong Feicheng Deyuan Chemical Co., Ltd., China) and low molecule polyamide hardener (Beijing Xiangshan United Assistant factory, China) were also used.

2.2. Design of the piezoelectric composite

Fig. 1 shows the process monitoring sketch map of cement hydration reaction. AFG3022B (Tektronix, America) signal generator was used to excite the emitting piezoelectric element, and TDS1002B (Tektronix, America) digital oscilloscope was used to collect the ultrasonic wave signal received by the receiving piezoelectric elements.

In order to monitor the early hydration reaction process of cement effectively, the emitting and receiving piezoelectric elements were designed and optimized by considering the characteristics of piezoelectric functional phase, matrix types and composite connectivity.

As for the emitting piezoelectric element, it should have large emitting power to acquire the strong emitting pulse signal. Meanwhile, considering the heat effect of high-power PZT-8 piezoelectric ceramic, therefore, medium power emitting PZT-4 piezoelectric ceramic was chosen as emitter. As for the receiving piezoelectric element, it should have broad frequency band, high receiving sensitivity and good acoustic impedance matching ability with cement paste. Therefore, piezoelectric composite was considered to be the suitable candidate. Receiving PZT-5 piezoelectric ceramic was used as functional phase, cement and cement/polymer (mixtures of cement powder, epoxy resin and hardener) were used as matrix to fabricate the piezoelectric composites, respectively. The reason of selecting cement and cement/polymer as matrix is that cement based piezoelectric composite can have good interface matching property with the cement paste, while the cement/polymer based piezoelectric composite will have better acoustic impedance matching property with the cement paste.

Usually, piezoelectric composite can be categorized into ten different types in accordance with the connectivity of each phase [18]. Considering the development and fabricating technique of cement based piezoelectric composites, 2-2 and 1-3 types piezoelectric composites were fabricated, respectively, aiming at exploring the optimal piezoelectric composite suitable for the cement hydration reaction monitoring.

It is well known that the higher the resonance frequency, the more obvious the attenuation effect of ultrasonic wave in medium. Presently, the resonance frequency of piezoelectric sensor used for nondestructive of concrete structure is usually between 20 kHz and 250 kHz. In this research, 100 kHz resonance frequency was chosen as emission frequency of the sensor. Considering the attenuation effect of cement paste on ultrasonic wave in different periods, the receiving resonance frequency of the piezoelectric composites can be less than 100 kHz. According to relationship between dimensions and resonance frequency of piezoelectric materials, the parameters of the piezoelectric composites were designed, as shown in Table 2.

2.3. Fabrication of piezoelectric composites

The piezoelectric composites were fabricated by cutting and filling technique, and the detailed fabrication sketch map is shown in Fig. 2.

First, WSQ50 diamond excircle cutter (Maike Material Processing Corporation of Shenyang, China) was used to cut the poled PZT-5 piezoelectric ceramic block according to the design parameter in Table 2. A series of piezoelectric ceramic plates/rods were cut along the polarization direction of the piezoelectric ceramic block. The polarization direction of the piezoelectric ceramic block is parallel to the thickness direction of the ceramic. During cutting, the piezoelectric ceramic block was not cut through the whole thickness, and a common base (approximately 1 mm) was left to hold all the ceramic plates/rods on it.

Secondly, KQ-100E ultrasonic cleaner (Kunshan Ultrasonic Equipment Co., Ltd., China) was used to wash the green bodies

Table 2
Designing parameters of receiving piezoelectric composites.

Number #	Dimensions of ceramic plate/rod (L × W × H) (mm)	Space between ceramic plate or rod (mm)	Matrix	Connectivity	Volume fraction of piezoelectric ceramic (%)
0	15 × 10 × 8.6	–	–	–	100
1	15 × 1 × 7.5	1	Cement	2-2	53.9
2	15 × 1 × 7.5	1	Cement/polymer	2-2	53.3
3	1 × 1 × 7.6	0.4	Cement	1-3	54.9
4	1 × 1 × 7.4	0.4	Cement/polymer	1-3	54.8